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Measuring sensible heat flux in plastic mulch culture with aerodynamic conductance sensors

Julie M. Tarara[a,*], Jay M. Ham[b]

[a]USDA-ARS, 24106 N. Bunn Road, Prosser, WA 99350, USA
[b]Department of Agronomy, Kansas State University, 2004 Throckmorton Hall, Manhattan, KS 66506-5501, USA

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Abstract

Black plastic mulch is commonly used in horticultural systems, but it may complicate the sparse crop energy balance by contributing to within-row advection. A steady state, heated foil technique was used to approximate the aerodynamic conductances to heat transport (g_h) of bare soil and black plastic mulch for 33 days. The test site was a field of 0.7 m wide raised beds covered with black plastic mulch and separated by 0.8 m wide strips of bare soil, with no crop present. From numerous point estimates of g_h and measurements of the temperature difference between the surface and the air, the sensible heat flux (H) was calculated independently for bare soil and plastic mulch. Conductance values ranged from 8 to 23 mm s^{-1} and no difference occurred between the mean g_h for mulch (17.0 mm s^{-1}) and that for bare soil (17.8 mm s^{-1}). The H estimated from conductance data was strongly linearly related, in a 1 : 1 ratio, to the H determined by independently solving the energy balance of plastic mulch. The conductance sensor method was used subsequently to estimate H from bare soil (H_{soil}). Sensible heat from plastic mulch (H_{mulch}) is the major source of H in the field because it is primarily a function of the net radiation of the plastic. Whereas H_{mulch} was always negative, with daily maxima consistently approaching -400 W m^{-2}, H_{soil} varied between -200 and $+50$ W m^{-2} according to surface wetness. Latent heat fluxes from the bare soil were <100 W m^{-2} when the surface was dry, and up to -400 W m^{-2} when the surface was wet. Managing the surface wetness of bare soil in a mulched field will not affect the energy balance of the mulch surface per se, but may reduce within-row advection, which is potentially detrimental to seedlings and transplants in plastic mulch systems.

Keywords: Plastic mulch; Energy balance; Sensible heat; Aerodynamic conductance

1. Introduction

Heterogeneous or 'patchy' surfaces, where plant canopies are sparse during part or all of the growing season, are common in agricultural systems. Many horticultural systems, such as orchards, vineyards, and nurseries, are sparsely vegetated during the entire growing season. Agronomic crops are sparse during the seedling stage. The physical environment around sparse vegetation is particularly important at this stage because plant productivity and yield represent integrated responses to conditions over the course of sparse crops have received less attention than those of uniform vegetation.

The primary challenge in solving the energy balance of sparse vegetation lies in partitioning the available energy at the surface (i.e., the sum of net radiation and soil heat flux ($R_n + G$)) into sensible (H) and latent (LE) heat fluxes. Measuring R_n and G in sparse vegetation can be arduous (e.g., McNaughton et al., 1992), although one can circumvent measurement limitations with well-developed physical models (Davies and Idso, 1979; Horton, 1989; Verhoef, 1995). Often, H and/or LE are modeled from gradients or profiles of temperature and water vapor above the surface, using several assumptions about the nature of energy transport to and from a homogeneous surface.

Surface similarity theory (Monin and Obukhov, 1954) relates gradients to fluxes via an 'eddy diffusivity' term (K_x), hence the designation 'K-theory'. K-theory treats the vertical fluxes of momentum, heat, and mass over a homogeneous surface as analogous. Several authors (Legg and Monteith, 1975; Raupach and Thom, 1981; Raupach and Legg, 1984; Kaimal and Finnigan, 1994) have noted that limitations in K-theory preclude its use within canopies and over sparse vegetation, and flux–gradient relationships are progressively less reliable as one approaches a vegetated surface, up to the point where they fail within a canopy. Kaimal and Finnigan (1994) (p. 90) state that the application of K-theory within canopies and over heterogeneous surfaces "has been abandoned by serious students."

Appropriate theories for heat and mass transport in sparse crops are few and still under development (e.g., Raupach, 1989), making it difficult to model the plant microclimate. However, theoretical research can benefit greatly from direct field observations of the key processes involved. Thus, measurement techniques that can provide numerous point measurements of energy transport in sparse crops are needed. Ultimately, such data will be useful in evaluating farming practices and validating models. One approach to partitioning H and LE from heterogeneous areas is to measure heat transfer coefficients for discrete surfaces (e.g., leaves, soil, and mulch). The transfer achieved popularity in plant and soil sciences, most notably for determining aerodynamic conductances of individual leaves (Parkhurst et al., 1968; Clark and Wigley, 1975; Smith et al., 1997). To date, heated foil techniques are the only direct methods that are practical for detecting small-scale, spatial variability in g_h on surfaces with differing properties and/or microenvironments. The steady state technique, which has been applied to leaves (e.g., Brenner and Jarvis, 1995) and to soil (McInnes et al., 1994), derives g_h from the difference in energy balances between two identical surfaces, one of which is heated continuously.

Mulching with plastic film is a horticultural practice that creates a patchy surface on the ground. Mulch film, typically, is installed by machine in 0.5–1.5 m wide strips, leaving bare soil between raised, plastic-covered beds. Plastic mulches are used for such purposes as raising soil temperatures, suppressing weeds, controlling soilborne pathogens, and conserving soil water. Ultimately, the desired microclimate effect of the mulch should direct the choice of plastic, its installation, and the duration of mulching. We used black plastic, the industry standard, as a test surface for measuring g_h and H because this mulch is used worldwide in agriculture and provides a simple, two-source system (i.e., plastic and bare soil) for sensible heat transport.

The objective of our study was to compare an estimate of H derived from sensor-based measurements of g_h with the value obtained by solving the energy balance of plastic mulch for H. Furthermore, the energy balance of the mulched field was partitioned into plastic and bare soil strips. As plastic mulch prevents evaporation from the underlying soil, we hypothesized that black plastic would be a considerable source of H. Finally, the surface energy balances were used to illustrate a potential microclimate created by black plastic mulch.

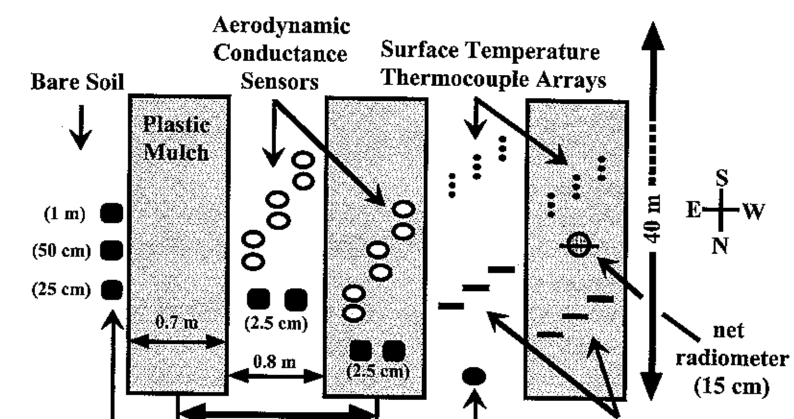
2. Materials and methods

2.1. Experimental site and meteorological measurements

40 m plot at the Kansas State University Horticulture Research Farm, south of Manhattan, KS (39.12° N, 96.35° W; 324 m above sea level). The plastic was stretched tightly over raised beds oriented N–S. Drip irrigation tape was installed simultaneously with plastic mulch, 5–8 cm below the soil surface and 15–20 cm east of the center of the bed. The mulch-covered beds were slightly trapezoidal, averaging 13 cm high and 70 cm wide at the top, and 75 cm wide at the base. The bare soil between mulched beds had a mean width of 83 cm, giving a center-to-center row spacing of 1.5 m. The soil type was Haynie sandy loam (coarse-silty, mixed, calcareous, mesic Mollic Udifluvents). A buffer strip (6 m wide) of bare soil surrounded the plot, which was bordered to the north and west by bare soil, to the east by another area of mulch-covered beds, and to the south by irrigated tree seedlings (<1 m tall). Fetch from the tree seedlings to the instrumented area was greater than 45 m.

Wind speed was measured at 1 m with a photo-chopped, three-cup anemometer (model 12102, R.M. Young Co., Traverse City, MI, USA). Wind speed and direction were measured at 2 m with a propeller anemometer/wind vane (model 5103, R.M. Young). Global irradiance was measured with an Eppley pyranometer (model 8-48, Eppley Laboratories, Newport, RI, USA). Shielded, aspirated, Type-T thermocouples (0.127 mm diameter (36 AWG)) measured air temperature at 2.5 cm above mulch and bare soil, and at 25 and 50 cm, and 1 m above the soil surface. Air temperature and relative humidity at 2 m were measured with a combined probe (HMP35A, Vaisala, Helsinki, Finland).

Surface temperature was recorded from three arrays of Type-T (copper–constantan) thermocouples (0.127 mm diameter, (36-AWG), Omega Engineering, Stamford, CT, USA) wired in parallel, creating a total of nine sensors per surface. Arrays were spaced evenly along a diagonal transect across the mulch-covered bed or across the bare soil. Bare thermocouple junctions were glued to the underside of plastic mulch, and soil-encapsulated thermocouples (SETs) depressed against the bare soil surface (Ham and Senock, 1992). The SET sensors were constructed with surface soil collected from the experimental area. Soil temperature at 2.5 cm was measured with the thermocouple of dual-probe heat capacity sensors (Tarara and Ham, 1997), three of which were installed along a diagonal transect across each surface. Spatial variation across the mulched bed or bare soil will be discussed with reference to the 'east', 'center', or 'west' locations on the surface. Signals from all instruments were scanned every 6 s, and averages computed every 12 min using a datalogger and two multiplexers (model CR7 and AM416, Campbell Scientific, Logan, UT, USA). Volumetric soil water content (θ_v) at 2.5 cm was measured every 6 h with dual-probe heat capacity sensors. Fig. 1 shows the layout of the instrumentation in the plot.



2.2. Aerodynamic conductance

We constructed 12 'surface conductance' sensors, half with circular, heated surfaces and half as identical, unheated controls, according to the design of McInnes et al. (1994), with a few modifications. Our sensors had two thermocouples rather than three: one to measure the temperature of the sensor surface and another 1 cm below the surface (Figure 1 in McInnes et al., 1994). The polystyrene foam chassis that supported and insulated the surface was 14 cm in diameter and 4 cm thick. The aluminum foil disk circumscribing the kaptan foil heater (No. KHLV-202/10; nominal resistance 19.5 Ω; Omega Engineering) was 7.18 cm in diameter, yielding a heated area of 0.00405 m^2. About 454 W m^{-2} of heat was applied to the heaters. In still air, the surface of a heated sensor was about 30°C warmer than that of an unheated sensor. Conduction through the sensor body was calculated from the thermal conductivity of polystyrene foam (0.033 W m^{-1} K^{-1}; Lide, 1997, pp. 12–97) and the temperature difference between the surface and 1 cm depth of polystyrene. Pairs of sensors were installed flush with the soil surface on diagonal transects across the mulched bed and bare soil (Fig. 1). To minimize contact resistance between sensor and mulch, the underside of the plastic was glued to the top of the sensor with a spray adhesive.

The heat transfer coefficient, g_h, can be approximated by

$$g_c = \frac{[-\varepsilon\sigma(T_+^4 - T_0^4) - (Q_+ - Q_0) + P_+]}{[\rho_a c_p (T_+ - T_0)]} \quad (1)$$

(Equation 4 in McInnes et al., 1994), where g_c is the aerodynamic conductance of the sensor (m s^{-1}), the subscripts $_+$ and $_0$ refer to the heated and unheated surfaces, respectively, T is surface temperature (K), Q represents heat conducted through the sensor body (W m^{-2}), P is power applied to the heater (W m^{-2}), and ε is surface emissivity. Sensor ε was 0.96 on bare soil, the value for the flat white paint, and 0.92 beneath plastic mulch, the value for black plastic. One expects g_c to vary with wind speed, surface geometry, and the the larger surface. Therefore, g_c includes the influences of turbulence structure and intensity on g_h.

Sensor pairs were checked for bias by installing them flush with the surface of bare, finely tilled soil, where the minimum fetch was 100 m in the direction of the prevailing wind. Sensor output was plotted against wind speed (u) at 1 m and corrected by linear regression against the sensor that fell closest to the mean behavior for the group. Data were excluded if $u < 0.5$ m s^{-1} to minimize the influence of errors from free convection at low wind speeds (McInnes et al., 1994).

2.3. Energy balance of a mulched field

The energy balance of a field with strips of black plastic mulch can be partitioned into two component surfaces, mulch and bare soil, whose energy balances are represented by

$$R_{n,m} + G_m + H_m = 0 \quad (2)$$

$$R_{n,s} + G_s + H_s + LE_s = 0 \quad (3)$$

where the subscripts $_m$ and $_s$ denote mulch and soil, respectively, R_n is net radiation, and G, soil heat flux. Positive values denote fluxes towards the surface, whereas negative values represent fluxes away from the surface. Energy stored by the surface is neglected.

Net radiation for the entire field ($R_{n,f}$) was measured with a net radiometer (REBS Q5.7.1, Radiation and Energy Balance Systems, Seattle, WA, USA) 2 m above the surface, situated such that its hemispherical 'view' consisted of equal portions of mulch and bare soil. A second net radiometer suspended 15 cm above the center of a mulch-covered bed measured $R_{n,m}$. On account of the low shortwave reflectance and high thermal conductivity of black plastic, the radiometer shadow did not affect output within detectable limits. Both radiometers had been factory-calibrated before the experiment, and when suspended over the same surface, their outputs agreed to within 0.5 W m^{-2} during daylight hours and to within 3 W m^{-2} at night. Raw measurements from the mulch radiometer (R_n^*)

properties of mulch and bare soil:

$$R_{n,m} = R_n^* + (c_{sw} + c_{lw}) \tag{4}$$

where $R_{n,m}$ is the corrected net radiation of the mulched surface. The correction factor $(c_{sw} + c_{lw})$ is composed of a shortwave component (c_{sw}) that accounts for the difference in reflectance between mulch and bare soil, and a longwave component (c_{lw}) that accounts for the differences in temperature and emissivity between the two surfaces:

$$c_{sw} = V_s R_s(\rho_s - \rho_m) \tag{5}$$

$$c_{lw} = V_s\left(\varepsilon_s \sigma T_s^4 - \varepsilon_m \sigma T_m^4\right) \tag{6}$$

Here, R_s is global irradiance (W m^{-2}), ρ_m (0.03) and ρ_s (0.23) are short wave reflectances (dimensionless), T_m and T_s are surface temperatures (K), ε_m (0.87) and ε_s (0.88) are emissivities (dimensionless) of the mulched bed and bare soil, respectively, and σ is the Stefan–Boltzmann constant (W m^{-2} K^{-4}). The surfaces were assumed to be isotropic. Dry soil ρ_s was used throughout the experiment. If we assume that the ρ_s of Haynie sandy loam falls by approximately half when the surface is wet, as indicated by Graser and Van Bavel (1982) for Lufkin fine sandy loam, the effect of using the dry soil ρ_s on $R_{n,m}$ is less than 10 W m^{-2}. Typical daytime values of c_{sw} were between 4 and 10 W m^{-2}, whereas c_{lw} was generally between −4 and −1 W m^{-2}. Around midday, the net correction to R_n^* was between 5 and 7 W m^{-2}, or about 1% of $R_{n,m}$ at its daily maximum (≈550 W m^{-2}). Table 1 lists the optical properties of mulch and soil that have been measured previously (Ham et al., 1993). Net radiation at the bare soil surface was calculated by difference, and weighted by the proportion of the field composed of bare soil:

$$R_{n,s} = \frac{R_{n,f} - 0.466 R_{n,m}}{0.534} \tag{7}$$

Soil heat flux on the surface was measured by the combination method (Kimball and Jackson, 1979). Heat flux plates (Model HFT-3, Radiation and Energy Balance Systems) were installed at 5 cm and dual-probe heat capacity sensors (Campbell et al., 1991; Tarara and Ham, 1997), at 2.5 cm. The dual probes were used to measure the change in heat storage in the 0–5 cm layer. The average rate of change in temperature at 2.5 cm was recorded every 12 min, and volumetric heat capacity was measured at 6 h intervals. Three sets of sensors were installed below each surface, evenly spaced along a diagonal transect across the raised bed or bare soil. Heat fluxes at the bare soil surface (G_s) and G_m were calculated as spatial averages of the three measurements, and G_f was calculated as the mean of G_s and G_m weighted by the proportions of the field composed of bare soil and mulch.

Given measurements of $R_{n,m}$ and G_m, H_m could be calculated as the residual of Eq. (2):

$$H_{m,eb} = -(R_{n,m} + G_m) \tag{8}$$

However, because of LE$_s$, H_s could not, likewise, be calculated as a residual of Eq. (3). Both H_s and H_m were calculated from conductance measurements and the temperature difference between the surface and air at 2.5 cm:

$$H_{x,c,i} = -g_{x,i}\rho_a c_p (T_{s,x,i} - T_{a,x}) \tag{9}$$

where the subscript $_x$ represents either mulch ($_m$) or bare soil ($_s$), $\rho_a c_p$ is the volumetric heat capacity of air (J m^{-3} °C^{-1}), and $(T_s - T_a)$ is the difference in temperature between the surface and the air. Spatial

Table 1
Optical properties of black plastic mulch and bare soil

Surface	Shortwave optical properties			Longwave optical properties	
	ρ	τ	α	ε	τ
Bare soil (dry)	0.23	–	0.77	0.88	–
Plastic mulch	0.03	0.01	0.96	[illegible]	[illegible]

variation in H was determined from T_s and g_c at each location ($_i$) along the diagonal transect. At all locations, T_a was the mean of two measurements above the given surface. The spatial mean of H ($\langle H_c \rangle$) for a given surface was calculated by

$$\langle H_{x,c} \rangle = \frac{\rho_a c_p}{3} \sum_{i=1}^{3} g_{x,i}(T_{s,x,i} - T_{a,x}) \tag{10}$$

The subscript $_c$ as in $H_{m,c}$ denotes the 'conductance method' of estimating H, as opposed to $H_{m,eb}$, the value obtained by independently solving the mulch energy balance (in Eq. (8)). Finally, LE_s was calculated as the residual term in Eq. (3).

The equation for estimating H_c from patchy surfaces, Eq. (9), closely resembles the bulk transfer equation developed for uniform surfaces:

$$H = h_r u_r \rho c_p (T_s - T_{a,r}) \tag{11}$$

where h_r refers to an 'interfacial transfer coefficient for sensible heat' (Brutsaert, 1982, p. 89). The magnitude of h_r depends on stability, fetch, and the reference height, r, where wind speed (u_r) and air temperature ($T_{a,r}$) are measured. In Eqs. (9) and (10), the g measured by surface conductance sensors is analogous to the product of h_r and u_r. Thus, direct measurement of g_c accounts for local variations in wind, surface roughness, and atmospheric stability. Essentially, the conductance sensors are heated anemometers flush with the soil or mulch surface.

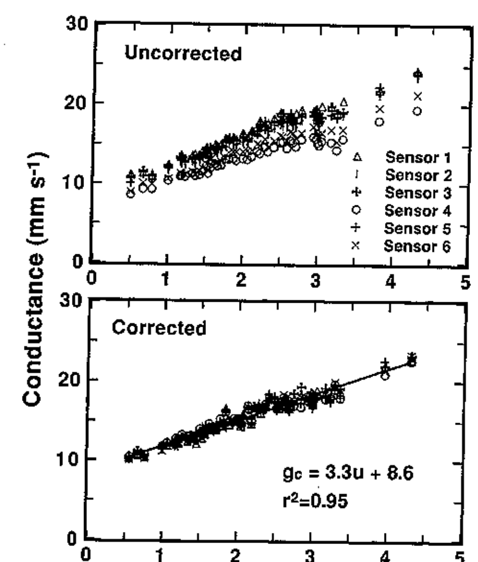
Using pairs of heated and unheated conductance sensors eliminates the measurement of T_a in calculating g_c (see Eq. (1)) because the energy balance of the unheated surface is subtracted from that of its heated counterpart. Consequently, the height or location of the appropriate T_a measurement for Eqs. (9) and (10) is not explicit. A 'correct' measurement must detect the temperature of the eddies responsible for the majority of heat transport. Therefore, for relatively smooth, non-vegetated surfaces, T_a should be measured close to the surface where the conductance sensors are installed. However, beneath sparse vegetation, most H may be due to large eddies originating above the crop in 'sweep–ejection' events (Paw U et al., 1992; Zermeño-Gonzalez and Hipps, 1997), and

3. Results and discussion

3.1. Performance of aerodynamic conductance sensors

Sensor-based aerodynamic conductance (g_c) is expressed in mm s^{-1} for numeric convenience and straightforward comparison with the results of McInnes et al. (1994). Output from the conductance sensors was corrected to that of sensor no. 2 which had a standard error of 0.57 as a function of u ($r^2 = 0.95$; $n = 226$), the smallest among the sensors when they were tested on finely tilled, bare soil (Fig. 2(a)). Corrected g_c was most nearly a linear function of u ($r^2 = 0.95$; SE $= 0.56$; Fig. 2(b)), suggesting a turbulent boundary layer over the sensors (Incropera and De Witt, 1990, p. 398).

Values of g_c from the test on bare, flat soil were similar to spatial averages reported for a ridge-tilled soil (McInnes et al., 1994). At $u = 0.5$ m s^{-1}, they found that $g_c \approx 8$ mm s^{-1}, and for our sensors, the same wind speed corresponded to conductances of about 10 mm s^{-1} (Fig. 2(b)). This difference was likely due to the relative influence of free convection



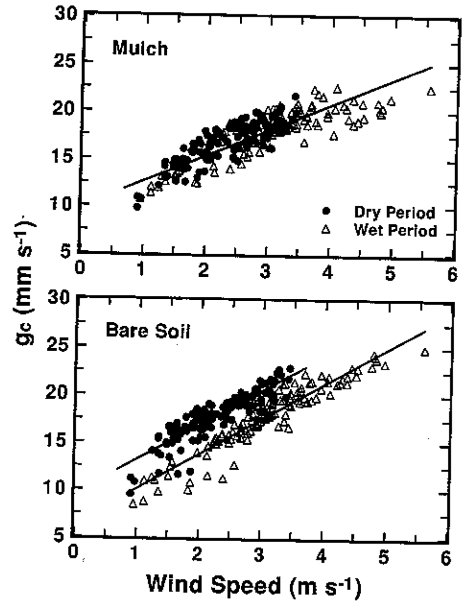


Fig. 3. Aerodynamic conductance of mulch-covered, raised beds and bare soil between beds as a function of wind speed. Lines represent predicted values by simple linear regression (mulch: $n = 624$; bare soil, dry: $n = 390$; bare soil, wet: $n = 234$).

from heaters of different characteristic dimensions and applied power densities. At $u = 4$ m s^{-1}, both groups of sensors gave $g_c \approx 20$ mm s^{-1}.

Contrary to the ridge-till results of McInnes et al. (1994), during our mulch experiment, g_c was not correlated with wind direction for either the mulched beds or the bare soil between beds (data not shown). However, our raised beds were aerodynamically 'smoother' than their ridge-till surface which had undulating geometry and an average furrow-to-ridge height of 24 cm. As our surface was relatively smooth, $g_{c,m}$ and $g_{c,s}$ varied similarly with u (Fig. 3). Data represent daytime values (9.00–17.00 LST) recorded every 12 min for 23 days ($n = 897$). Overall means were 17.0 mm s^{-1} for mulch, and 17.8 mm s^{-1} for bare soil. However, similar means do not suggest that a simple wind function should be used to predict g_c on patchy surfaces. On the contrary, introducing plants to a mulch system will alter flow over both surfaces, and that effect will vary with crop size. The strength of the heated foil method is that sensors can be placed on small areas that differ in surface characteristics, and therefore, can measure spatial variability in g_h, which McInnes et al. (1996) demonstrated across clean-tilled rows in a commercial vineyard.

Changes in stability and buoyancy associated with changes in local weather may explain some difference in the exact wind functions between 'dry' (day of year (DOY) 248–258) and 'wet' (DOY 272–280) periods of the study in the case of bare soil (Fig. 3(b)). Although we did not know the turbulence regime during the experiment, the wet period followed several days of heavy rain (≈60 mm (total)) and was characterized by only slightly higher wind speeds, but lower air temperatures than the dry period. For example, average daytime wind speeds at 1 m were 2.4 m s^{-1} (±0.5) on DOY 248 and 2.8 m s^{-1} (±0.4) on DOY 272, representative days for the two periods. The average daytime (9.00–16.00 LST) Richardson number was −2.2 on DOY 248 compared to −1.1 on DOY 272, indicating weak horizontal motion on both days, but stronger convective instability over the field when the soil surface was dry (DOY 248; Oke, 1987, p. 382). During the dry period, greater surface–air temperature differences (Table 2) over bare soil increased buoyant forces, enhancing g_h at all wind speeds (Verma and

Table 2
Average daytime values (9.00–17.00 LST) of surface and air temperatures recorded during the dry (DOY 248–258) and wet (DOY 272–280) periods of the experiment. Numbers in parentheses represent the daytime ranges

Bare soil surface condition	Temperature (°C)				
	Air (1 m)	Mulch		Bare soil	
		Surface	$(T_s - T_a)$	Surface	$(T_s - T_a)$
Dry	25.0	42.1	17.1		

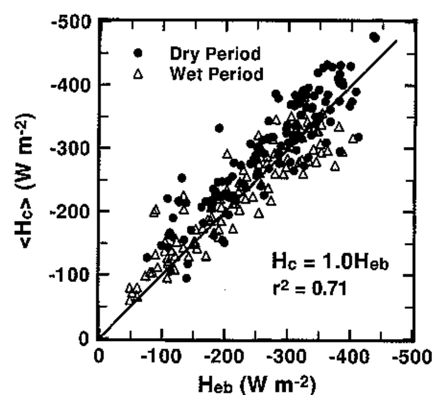
Barfield, 1979). Over plastic mulch, surface–air temperature differences did not change substantially with the wetness of the bare soil surface, hence the more consistent relationship between g_c and u (Fig. 3(a)).

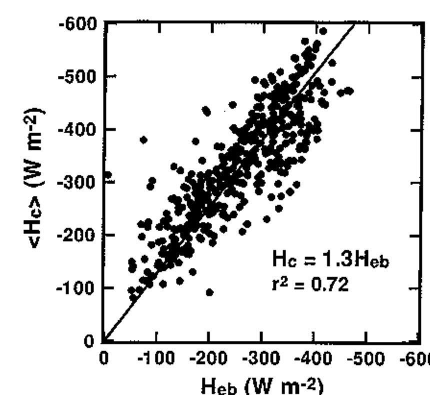
One theoretical concern related to the use of heated foil sensors is that the characteristic dimension of the sensor is less than that of the surface of interest (e.g., mulched bed). Sample calculations showed that under laminar flow, a heated, flat plate with the same characteristic dimension as our conductance sensors (7 cm) would be expected to enhance g_c by ≈30% compared to that of the larger, unheated surface (i.e., mulch, ≈72 cm) because of a thermal boundary layer created by the heated spot (Bejan, 1995, pp. 55–57). However, in the field, turbulent flow governs transport from both sensors and the larger surface, and g_c may approach the value of g_h, depending on the scale and intensity of the turbulence (Chen et al., 1988).

3.2. *Estimates of sensible heat flux: H_c and H_{eb}*

The utility of the aerodynamic conductance sensors is not only in approximating g_h on patchy surfaces, but ultimately in determining H. Considering the number of measurements involved in calculating H_c (see Eqs. (1),(9) and (10)) and H_{eb} (see Eq. (8)), the relationship between the two is excellent and strongly linear (Fig. 4; $n = 897$). As $H_{m,eb}$ is an integrated value across the mulched bed, the spatial average of $H_{m,c}$ was computed (see Eq. (10)). No significant difference occurred in regression slopes between dry and wet periods. On account of the agreement between $H_{m,c}$ and $H_{m,eb}$, we extended the relationship to the bare soil between rows, and defined $H_{s,eb} = H_{s,c}$.

The independent means of measuring H_m (see Eq. (8)) allowed us to evaluate H_c at different reference heights. Solving Eq. (10) for $H_{m,c}$ with air temperatures recorded at 2 m gave an $H_{m,c} : H_{m,eb}$ ratio of $1.3:1$ ($r^2 = 0.72$; $n = 897$; Fig. 5). However, it is unclear whether temperatures recorded at screen height would represent the actual temperature of the air responsible for transport from the surface. Over a smooth patchy surface like our mulched field, many small-scale eddies of the order of the height of the roughness elements (i.e., the mulched beds) may dominate transport, and therefore, time-averaged values of T_a at 2.5 cm may be representative of the eddies that are responsible for H. Conversely, in a well-developed plant canopy, most of the heat transport may be accomplished by intermittent sweep–ejection events occurring when a large eddy from the overlying atmosphere momentarily sweeps warm, dry air into the canopy, mixes with the cooler, moister canopy air, and is ejected back into the free stream. In this case, time-averaged values of T_a at screen height may represent the transporting eddies more accurately than do T_a measurements near the soil surface. Sparse crops probably fall between these two extremes, with more mixing than occurs in a closed canopy and with H dominated by a range of eddy sizes. The length scale





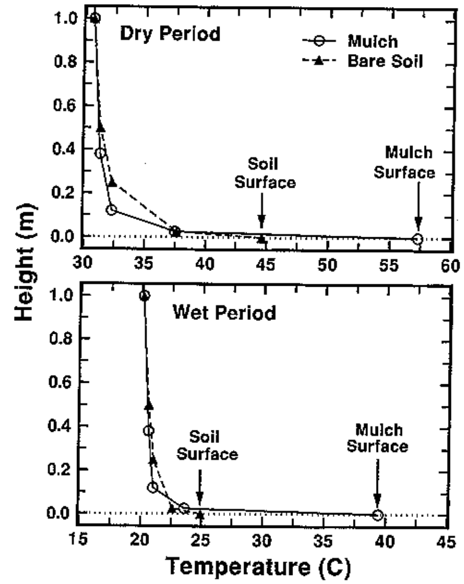


Fig. 6. Temperature profile from mulch and bare soil to 1 m above the surfaces at 13.00 LST on DOY 248 (dry) and DOY 272 (wet).

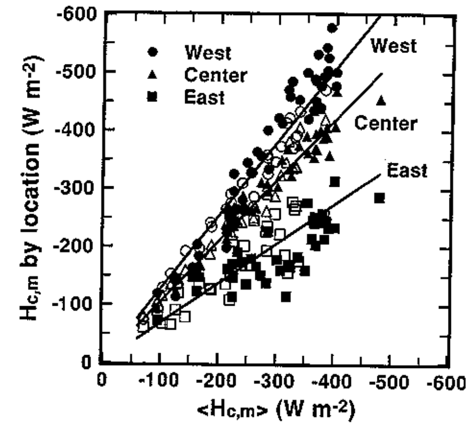


Fig. 7. Sensible heat flux from mulch ($H_{c,m}$) by location across the bed plotted against the spatial mean ($\langle H_{c,m}\rangle$). Solid symbols represent data from the dry period and open symbols represent data from the wet period. Lines represent predicted values of each position against the spatial mean by simple linear regression ($n = 897$).

of our conductance sensors may have been of the same order as that of the eddies dominating transport in the mulch system, leading to the 1 : 1 result when T_a was measured at a height also on the same scale as the transporting eddies. The 1.3 : 1 H_c : H_{eb} ratio suggests that T_a at 2 m was not representative of the temperature of the small, high frequency eddies dominating H in this system.

Most of the variation in H_c can be accounted for by the variation in ($T_s - T_a$) (82% for mulch; 97% for bare soil), and H_c was not a strong linear function of g_c. Eqs. (9) and (10) assume that T_a is measured close enough to the surface so that fluxes do not diverge between the surface and the measurement points. The large temperature gradient above black plastic mulch and dry bare soil (Fig. 6) supports our use of near-surface (2.5 cm) measurements of T_a. Regardless of the wetness of the soil surface, the mulch temperature was about 20°C warmer than the air at 2.5 cm, whereas the bare soil–air ΔT varied with LE_s. The large temperature gradient illustrates that black plastic

contribute to spatial variation in energy fluxes, particularly in drip-irrigated systems. Between DOY 248 and DOY 258, $\theta_{v,m}$ at 2.5 cm ranged from 0.2 to 0.25 at the east and center locations (higher along the drip line), but remained at around 0.1 at the west location (data not shown). Spatial variation in G_m (Fig. 8(a)) was much smaller than that in H_m, even though a large gradient occurred in ρc_p from the east to the west sides of the bed. Variation in $T_{s,m}$ followed the same trend as that in H_m (Fig. 8(b)). Further investigation of spatial variation in H across the mulched bed would be more informative in the presence of a crop that would shade an increasing portion of the surface during the growing season.

In summary, these results support the use of aerodynamic conductance sensors for approximating the g_h of patchy surfaces, and its subsequent use in calculating H_c, provided that careful measurements of ($T_s - T_a$) are made. On sparsely vegetated surfaces, T_s sensors must obviously be located so that the sampling points are subjected to the same incident radiation as their associated conductance sensors. A 1 : 1 ratio was established between H_c and H_{eb} when

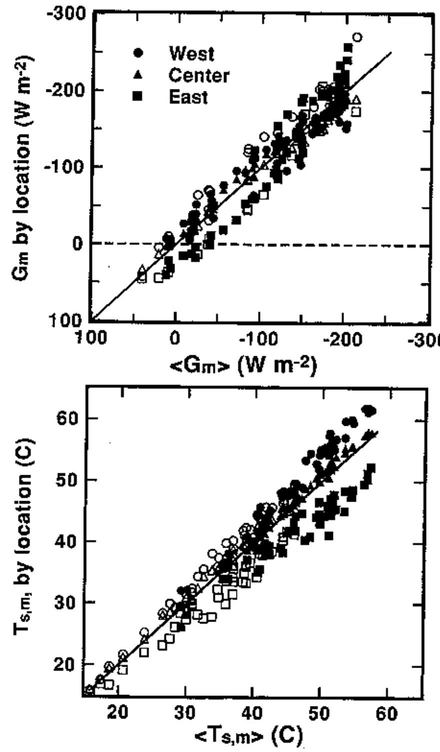


Fig. 8. Soil heat flux at the mulch surface (G_m) by location across the bed plotted against the spatial mean ($\langle G_m \rangle$; top). Surface temperature of mulch ($T_{s,m}$) by location across the bed plotted against the spatial mean ($\langle T_{s,m} \rangle$; bottom). Solid symbols represent data from the dry period and open symbols represent data from the wet period. Lines are 1 : 1 plots.

method of checking H_c is available and a sparse crop creates an aerodynamically rough surface, one may, instead, need to approximate the temperature of the free stream by measuring T_a at screen height, and given a measurement of T_a at 2 m, H_c may overestimate H_{eb} by as much as 30%.

3.3. Patchy surface energy balances: plastic mulch and bare soil

Energy balances for mulch and bare soil on DOY 248 illustrate the differences between plastic and bare soil surfaces during the dry period (Fig. 9(a),

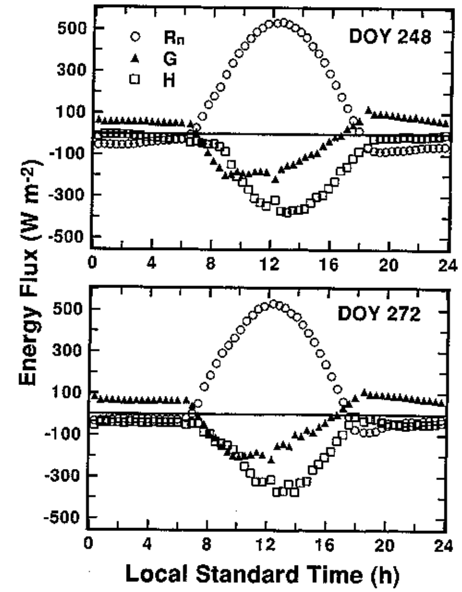
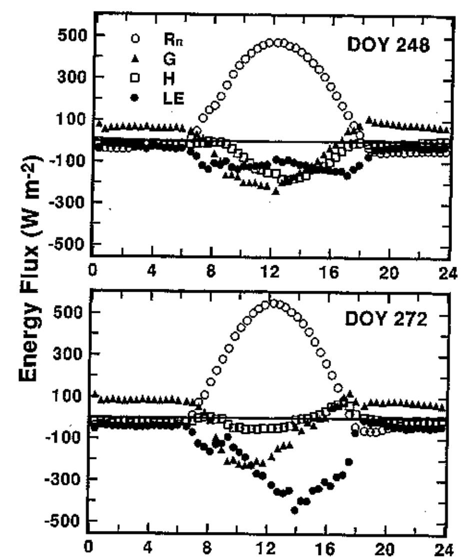


Fig. 9. Diurnal energy balance of black plastic mulch on DOY 248 when the bare soil surface was visibly dry, and on DOY 272 when the bare soil surface was visibly wet.

vapor diffusion rather than by solar radiation on the surface. Midday R_n was slightly higher on the mulch ($\approx$525 W m^{-2}) than the bare soil surface



(≈490 W m^{-2}), whereas G_m and G_s were nearly identical. Both mulch and bare soil surfaces were sources of H, but H_m exceeded H_s throughout the day, and did so by more than 150 W m^{-2} near midday. Under these and similar conditions, a large amount of sensible heat could converge on seedlings from both mulch (up to 400 W m^{-2}) and bare soil (up to 225 W m^{-2}), which could evoke high rates of transpiration. This type of microclimate is likely to induce heat stress in seedlings, particularly during the first weeks after transplanting when the roots may be unable to satisfy evaporative demand at the leaf.

Surface energy balances on DOY 272 (Fig. 9(b), Fig. 10(b)) illustrate a wet period characterized by bare soil with a visibly wet surface. The energy available to mulched and bare soil surfaces ($R_n + G$) was similar. During the afternoon, the bare soil shifted from a source to a mild sink of H. At its highest, LE_s was of the same magnitude as H_m. In this situation, mulch could still potentially subject seedlings to a large amount of H, but bare soil would not add to that evaporative burden.

As H_m is largely due to $R_{n,m}$, the energy balance of mulch was similar whether the bare soil surface was dry or wet (Figs. 9 and 10). Global irradiance was consistently high during both periods of the experiment, exceeding 800 W m^{-2} around midday on days with clear skies (data not shown). Until a crop is large enough to shade a significant fraction of the plastic, the mulch energy balance would dominate that of the seedlings. Regardless of the surface condition of the bare soil between mulched beds, one would expect substantial convection from black plastic towards the seedlings.

Consider the energy balance of the entire field (Fig. 11). With a dry bare soil surface, the field is a larger source of H than when the bare soil is wet. Table 3 lists total daytime energy fluxes (9.00–17.00 LST) for mulch, bare soil, and the field under dry and wet conditions. The largest differences are in H_s, H_f, and LE. In addition to managing soil surface wetness (LE_s), the field energy balance could be moderated by choosing a plastic with optical properties such that $R_{n,m}$ would be less than that of black plastic, thereby

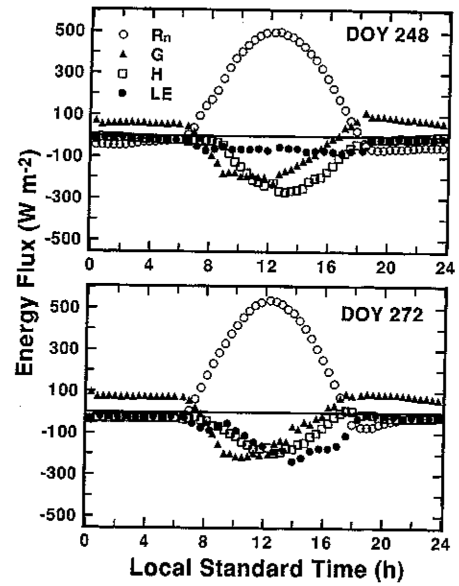


Fig. 11. Energy balance of a mulched field with dry and wet surface conditions of the bare soil.

seedling canopy. The best management scenario will depend on the purpose of the mulch, local conditions, and the crop.

Table 3
Total daytime energy fluxes to and from plastic mulch, bare soil, and integrated values for the entire field under representative dry (DOY 248) and wet (DOY 272) days, as indicated by surface condition of bare soil

Energy balance component	Daytime flux (9.00–17.00 LST) (MJ m^{-2} per day)	
	Dry	Wet
R_n		
Mulch	10.74	9.33
Soil	9.08	8.52
Field	9.85	8.90
G		
Mulch	−3.18	−2.90
Soil	−3.26	−2.69
Field	−3.22	−2.79
H		
Mulch	−8.37	−6.55
Soil	−4.41	−1.46
Field	[illegible]	[illegible]

4. Conclusions

Relationships between wind speed and surface conductance, and comparison of our results on bare, flat soil with those of McInnes et al. (1994) suggest reliable performance by our conductance sensors. Aerodynamic conductance sensors of this design are promising tools for measuring spatially variable conductances that characterize patchy surfaces and that must be estimated to calculate energy fluxes from these surfaces. As flow in the field is turbulent, the small thermal boundary layer induced by the heated foil can be sufficiently disturbed such that g_c approximates the actual value of g_h, even though the length scale of the sensors is less than that of the mulched beds. The agreement between conductance sensor H and energy balance derived H was excellent, and overall, a 1 : 1 relationship was found when near-surface (2.5 cm) measurements of air temperature were used.

Strips of black plastic mulch are considerable sources of sensible heat, irrespective of the energy balance of bare soil between rows. Bare soil between mulched beds can be a source of H when its surface is dry. Consequently, substantial H can converge on seedlings from more than one discrete surface in this system. Advection can be reduced by irrigating the surface of bare soil, thereby transforming it into a sink for H, which our data show during the wet period of the study. However, because plastic mulch is virtually impermeable to water and water vapor, H_m depends directly on $R_{n,m}$ which approached a daily maximum of 550 W m^{-2} during the experiment. To decrease H_m, one must reduce $R_{n,m}$, which could be achieved by altering the optical properties of the plastic.

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